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# An improved method to monitor the health of seagrass meadows based on kriging

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## A B S T R A C T

This paper focuses on the spatial pattern of the shoot density of the seagrass *Posidonia oceanica* through kriging methods. Kriging is a group of geostatistical techniques to predict the value of a field at an unobserved location from observations of its value at nearby locations. The results of an ordinary kriging of both raw values of shoot density and normalized shoot density with reference to a density vs. depth model (Dn) were compared. Results confirmed the existence of spatially organized parameters other than depth that influence patterns of *P. oceanica* shoot density. Although still requiring additional testing for complete validation, Dn mapping appears to be a valuable tool to (1) infer causes for the meadow's condition and to design a cost-effective field survey; (2) define areas where protection policies should be undertaken.

## Keywords:

Shoot density

Depth

Monitoring

Mapping

*Posidonia oceanica*

Mediterranean

## 1. Introduction

Seagrass meadows are considered amongst the most important marine ecosystems, from the points of view of biodiversity, ecology and economics (Duffy, 2006). For this reason and for coastal management purposes, a significant effort has been devoted worldwide to the mapping of seagrass meadows (e.g. Frederiksen et al., 2004a; Leriche et al., 2004; Fornes et al., 2006; Pergent-Martini et al., 2006). Most of these maps only deal with the spatial extent of the meadows and do not provide information about the health of the *Posidonia oceanica* meadow, in contrast with maps including qualitative and quantitative data (e.g. healthy beds vs. those in bad condition, expansion vs. regression trend, continuous vs. patchy beds, dense vs. sparse and ecological indices addressing the bed's health) (Pasqualini et al., 1999; Ward et al., 2003; Frederiksen et al., 2004b; Garono et al., 2004; Montefalcone et al., 2006).

Kriging is a group of geostatistical techniques based on stochastic modelling and a linear interpolator used to predict the value of a field at an unobserved location from observations of its value at nearby locations. This technique provides a detailed description

of the structural characteristics of natural systems (Cressie, 1991). The first map of *P. oceanica* shoot density, interpolated via kriging from raw data, was presented by Scardi et al. (1989) and new maps were produced in the following years (Pergent, 1990; Pergent et al., 1995a; Scardi et al., 2006; Zupo et al., 2006a,b). Shoot density changes occur in *P. oceanica* beds, both in time and in space (Panayotidis et al., 1981; Borg et al., 2006; Zupo et al., 2006a,b). The decrease in density with depth is a general feature of *P. oceanica* meadows (Augier and Boudouresque, 1973; Panayotidis et al., 1981; Pergent and Pergent-Martini, 1988) related to the decline of irradiance and temperature along the depth gradient (Pirc, 1984; Zimmerman et al., 1994; Ruiz and Romero, 2001). Pergent et al. (1995b) and Pergent-Martini et al. (1999) studied the variations of *P. oceanica* shoot density with depth on 400 sites across the western Mediterranean Sea. They found that depth explained 54% of the spatial variation in shoot density. The model they fit to shoot density measurements in relation with depth can be used to assess if shoot density measured at a given depth is low, normal or high. Most Mediterranean laboratories use this standardized scale of evaluation. According to many authors (Pergent et al., 1995b; Buia et al., 2000; Ruiz and Romero, 2001; Gobert et al., 2003), other parameters explaining shoot density variability could be water turbidity, pollution, water movement, substratum typology and plant stonolization pattern, but no analyses or data have been provided to support the hypothesis of the influence of spatially structured factors on shoot density patterns.

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The aim of this paper is to present a method for analysing spatial seagrass shoot density distribution eliminating the depth effect that masks other pattern of ecological relevance. To determine if there is residual non-random spatial structure after the effect of depth on shoot density has been accounted for, two interpolated maps of the raw and normalized shoot density of a Mediterranean *P. oceanica* meadow were developed and compared.

## 2. Methods

### 2.1. Study area

The study area (Saint-Cyr Bay; approximately 4 km<sup>2</sup>) is located to the east of Marseilles (Provence, France; 43°10'N–5°41'E). The *P. oceanica* meadow occupies a wide depth range (from a few meters down to 33 m deep) for a surface area of approximately 195 ha. *P. oceanica* grows mostly on sandy substrate with the exception of two rocky areas (Saint-Louis Cape and La Madrague harbour). Human impact at the study site originates from the port facilities of La Ciotat (5 km westwards), two small pleasure boat harbours, coastal leisure activities, trawling and a pipe discharging treated sewage at depth of 40–50 m (23,000 population-equivalent). Such impacts may lead to the appearance of dead matte areas (dead matte is constituted by the intertwined dead rhizomes the interstices of which are filled with sediment). The meadow's upper and lower depth limits and areas without *P. oceanica* (intermattes) were mapped in a GIS (Geographic Information System) software ArcView 3.2®, using methods detailed in [Leriche et al. \(2006\)](#).

### 2.2. Measuring the shoot density

The shoot density is the mean number of living *P. oceanica* shoots per unit surface area. Only bottom areas occupied by the meadow are taken into consideration. Measurement of shoot density was performed on 34 sites; most of these sites are located along transects (T1 through T5). Sampling design was defined to cover the meadow and environmental conditions in the area as uniformly as possible, with transects crossing the meadow from deep to shallow limits, on sandy and rocky substratum. Five counts were performed within 20 cm × 20 cm plots at each sampling point at all sites but one (three counts). This protocol follows recommendations found in the literature ([Marcos-Diego et al., 2000](#); [Pergent-Martini et al., 2005](#)). It is also similar to the protocol applied by [Pergent et al. \(1995b\)](#) and [Pergent-Martini et al. \(1999\)](#) to collect the data used to generate the regression model of shoot density with depth which was used in the present study. Shoot density was expressed in number of shoots per square meter. The 34-site median standard deviation of the measurements was of 53 shoots per square meter. For each site, the measurements were averaged to give the “raw” shoot density value of the site.

### 2.3. Raw shoot density kriging

The steps in the kriging process are (1) build a semi-variogram from observed data (experimental semi-variogram) corresponding to the semivariance of value differences in relation to spatial distance between sites; (2) fit a function (theoretical semi-variogram) to the experimental semi-variogram, using one or more specific models (spherical, exponential, etc.); (3) from the theoretical semi-variogram build the kriging system; (4) solve it to get the optimal weights for the linear interpolator.

Several anisotropic (*i.e.* direction dependant) theoretical semi-variogram models were performed, fitted by least squares regression of the experimental semi-variogram that was computed on raw data (average of the five measurements taken at a site, expressed per square meter) by means of Geostatistical Analyst®

**Table 1**

Values of the parameters of semi-variogram fitting; sill: limit of the semi-variogram tending to infinity; nugget value: the semivariogram discontinuity at the origin; range: the distance in which the semi-variogram reaches the sill. Due to the anisotropy both a major range with its direction and minor range (orthogonal to major direction) are indicated.

	Ordinary kriging on raw data of shoot density	Ordinary kriging on normalized shoot density (Dn)
Major range	2420 m	2420 m
Direction	350°	350°
Minor range	1145 m	1015 m
Nugget	0.00	0.01
Sill	84,800	1.79

(extension of Arcview 8.3®). The best fitted model (validated by scatter plots of predicted values by cross-validation vs. true values) was a classical spherical semi-variogram ([Webster et al., 2007](#)), and characterized by a small number of parameters. No nugget effect (discontinuity at the origin representing non-spatial pure random effect) was included, which is consistent with the shoot density kriging calibration found in the literature (*e.g.* [Zupo et al., 2006a](#)). An ordinary kriging of raw data, that assumes stationarity with a constant but unknown mean ([Cressie, 1991](#); [Webster et al., 2007](#)) was then performed with the same software.

### 2.4. Normalized shoot density modelling and kriging

The regression of shoot density with depth in relatively undisturbed sites could be modelled as:

$$y = -254 \ln(x) + 1045.8 \quad \text{with } sd = 112 \quad (1)$$

where  $y$  is the shoot density (number m<sup>-2</sup>),  $x$  is the depth (m) and  $sd$  is the standard deviation of the curve from [Pergent et al. \(1995b\)](#) and [Pergent-Martini et al. \(1999\)](#).

In order to remove the effect of depth on *P. oceanica* shoot density values, the normalized density (Dn), *i.e.* the deviation from the theoretical mean density (reference level) at a given depth, was calculated. This has been done for each studied site in Arcview 8.3® database with the equation:

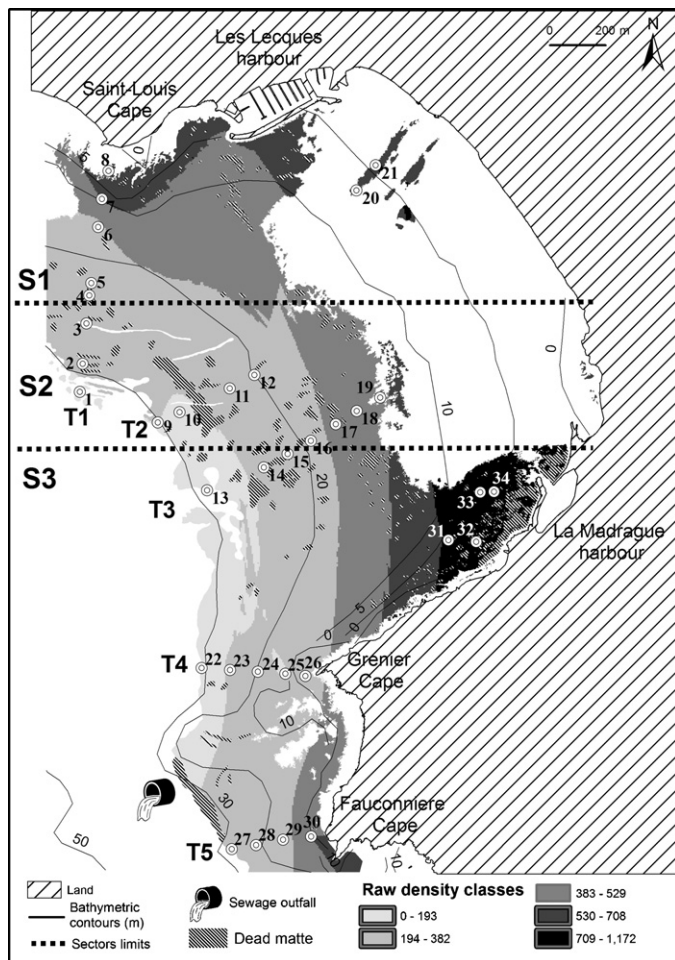
$$Dn = \frac{(D - [-254 \ln(x) + 1045.8])}{sd} \quad (2)$$

where Dn is the normalized shoot density at a site,  $D$  is the mean of the five measurements of shoot density taken at a site in the study area and  $x$  is depth of the site.

Because the anisotropy still remains, the geostatistical procedure applied on normalized data was the same as on raw data. Five classes were considered: medium density (variance from the mean <|0.1|, meaning value of shoot density close to the value expected from the model of density variation with depth), low and high (|0.1| < variance from the mean <|0.5|) and very low and very high (variance from the mean >|0.5|).

## 3. Results

Parameters of the semi-variogram fitted on both raw and normalized shoot density data are presented in [Table 1](#). A semi-variogram presents a flat region where the semivariance no longer increases. The distance where the model first flattens out is known as the range ( $x$ -axis) and the value at which the semivariogram model attains the range ( $y$ -axis) is called the sill. In this study, because of anisotropy the “range” characteristics are given through three parameters: a major range with its direction and a minor range on the orthogonal direction. Except for the sill, which models data variance, parameters for raw and normalized shoot density data are very close. The nugget values (*i.e.* height of the jump of the

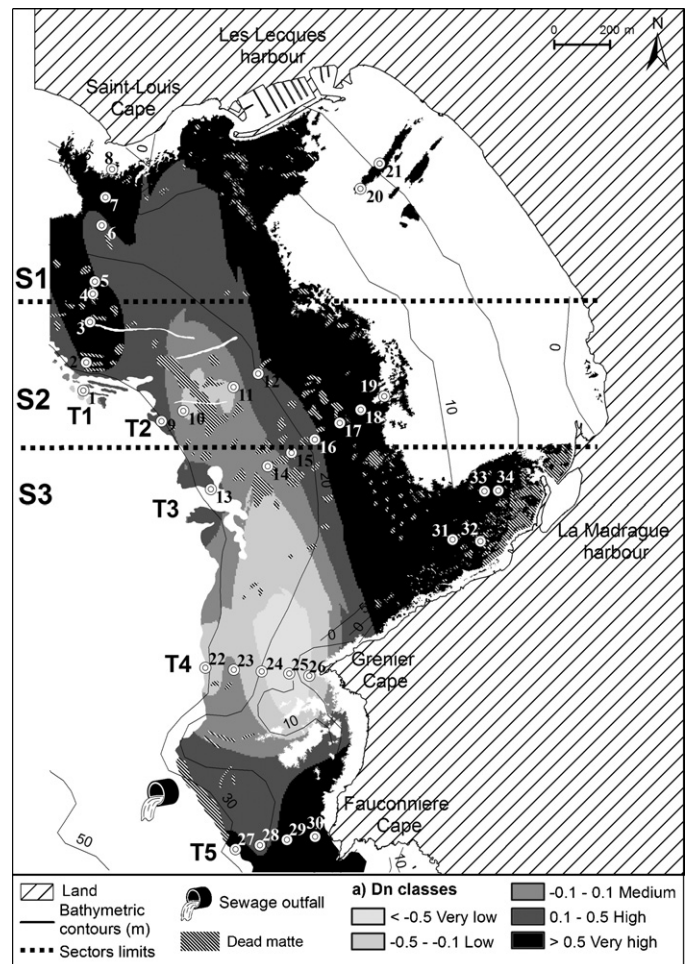


**Fig. 1.** Distribution of *Posidonia oceanica* and surface values of raw shoot density values (number  $m^{-2}$ ) as modelled by ordinary kriging. Sites where shoot density has been measured (double circle) from the transects (T) of each sectors (S), are pointed out on the map. Jenks' natural breaks classification scheme was chosen for raw density classes' definition as it identifies break points by picking the class breaks that best group similar values and maximize the differences between classes.

semivariogram at the discontinuity at the origin) are equal or close to zero.

The ordinary kriging of raw data of shoot density (Fig. 1) confirms the existence of a marked gradient of shoot density values which follows the depth gradient. This gradient exists over the entire study area. Raw shoot density values are particularly high (530–1172 shoot  $m^{-2}$ ) along the north and south coasts (0–10 m depth) and decrease with depth to 30 m.

The result of ordinary kriging of Dn (Fig. 2) shows a different spatial pattern. The *P. oceanica* meadow of sector 1 (S1) is classified as high or very high density (Dn values between 0.1 and 0.5 and above 0.5 respectively, i.e. greater than the mean density). Sectors 2 (S2) and 3 (S3) are less homogenous. In areas shallower than 20 m depth, the entire meadow in S2 has high or very high values of Dn. Between 20 and 30 m depth, the meadow is classified as medium density (Dn values around zero, i.e. close to the mean density) and high density, with the exception of a patch of low density (Dn values between  $-0.5$  and  $-0.1$ , i.e. less than the mean density) around the biggest area of dead matte mapped in the study area (sites 10 and 11). Shallow meadow in the northern part of the S3 (sites 31–34) is classified as high or very high density, as is the southern part of the sector (T5). An extensive oval-shaped area (oriented north–south) between 10 and 30 m depth has low and very low values of Dn. The southern limit of this area is located in the middle of a zone



**Fig. 2.** Distribution of *Posidonia oceanica* in Saint-Cyr Bay and surface values of normalized shoot density (Dn) values as modelled by ordinary kriging. Sites where shoot density has been measured (double circle) from the transects (T) of each sectors (S), are pointed out on the map.

that exhibits a lot of intermattes (between Grenier and Fauconniere Capes). The deep limit of the meadow in S3 is classified as medium to high density, with the exception of a small part around site 22 that has a low density.

#### 4. Discussion

The method we propose here was able to eliminate depth effect and proved that the part of the density variation not explained by the depth parameter (46% according to Pergent-Martini et al., 1999) is spatially structured (not a random phenomenon) and cannot be attributed to measurement errors or spatial sources of variation at distances smaller than the sampling interval (nugget value close to zero). The seeming persistence of a depth effect along transect T3 could suggest that the model of shoot density decline with depth from Pergent et al. (1995b) and Pergent-Martini et al. (1999) is not fully applicable at the present study site. However this is not supported by data from all other transects for which no pattern of decrease of shoot density with depth is observed. Results indicate that half of the meadow exhibits high or very high Dn values. We have to consider two different interpretations of these results. The first is that the method we present in this paper is correctly calibrated by Eq. (2), meaning that the *P. oceanica* meadow of the Saint-Cyr Bay is a particularly healthy ecosystem, at least in its Northern, Southern and shallower areas which has higher density

values than the Mediterranean average. The second interpretation would be that Eq. (2) tends to underestimate the density values. Even if scientific scuba-divers described this *P. oceanica* meadow as in quite good condition (Bonhomme P., Bernard G., Cadiou G. pers. com.), it is clear that this new approach now needs to be tested and possibly recalibrated on a set of other sites across the Mediterranean coast.

This work shows that maps of normalized density of shoots (Dn) are more interesting than presence-absence or even raw shoot density interpolation maps. A normalized map highlights the information otherwise hidden by depth contained in raw shoot density data, and discriminates between healthy areas and potentially unhealthy seagrass patches. This new mapping approach shows great potential as a valuable tool to help investigate the possible causes for the meadow's condition. For the present study site for example, various natural or anthropic factors may be proposed to explain the remaining spatial structure of Dn and will need further investigation. The most obvious ones would be trawling and boat anchoring. The possible effects of the nearby sewage outfall on *P. oceanica* meadow health must also be considered. As the impacts of these two kinds of anthropic factors can be mitigated, it may be worthwhile using the technique described here to delimit areas where field sampling may be useful, and conservation policies should be undertaken.

This new approach is no more time consuming than the classical mapping methods, and it provides data of greater value and usefulness for seagrass meadows managers and other stakeholders.

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